THERMAL FEATURELESS SPECTRUM: EVIDENCE FOR BARE STRANGE STARS?

R.X. XU

School of physics, Peking University, Beijing 100871, China; rxxu@bac.bku.edu.cn
Draft version February 1, 2008

ABSTRACT

Motivated by trying to understand the absence of spectral lines in the thermal components of the X-ray compact sources observed recently by Chandra or XMM, we propose that these sources could be simply bare strange stars. The formation, cooling, and thermal photon radiation of bare strange stars have been investigated. It is suggested that thermal featureless spectrum could be a new probe for identifying strange stars.

Subject headings: elementary particles — pulsars: general — stars: neutron — dense matter

1. INTRODUCTION

To affirm or negate the existence of strange star is an exciting and meaningful approach to guiding physicists in studying the quantum chromodynamical (QCD) nature of strong interaction. With regard to those three possible ways of finding strange stars (see, e.g., Xu & Busse 2001, for a short review), a *hard* evidence to identify a strange star might be found by studying only the surface conditions since the other two avenues are subject to many complex nuclear and/or particle physics processes poorly known. New advanced X-ray detectors, the Chandra and the XMM, increase the possibility of discovering the surface differences between neutron star (NS) and bare strange star (BSS) since both exteriors of NS and BSS should be thermal X-ray radiators.

Many calculations, first developed by Romani (1987) and then by others (e.g., Zavlin et al. 1996), show that spectral lines form in the atmospheres of NS or crusted strange stars (CSS), which should be detectable with the spectrographs on board Chandra and XMM. However *none* of the sources reported recently has significant spectral features in the observations with Chandra or XMM. These sources are collected in Table 1, the spectra of which can be well fitted with blackbody models for the thermal components. An observation presented by Marshall & Schulz (2002) indicates still no significant line feature even in the pulse-phased spectra over the 0.15-0.80 keV band, which does not favor both models of atmospheres of heavy elements or pure hydrogen. Although this discrepancy could be explained for some of the sources by assuming a low-Z element (hydrogen or helium) photosphere or by adjusting the magnetic field, a simple and intuitive suggestion, which will be addressed in this *Letter*, for the explanation is that these "neutron stars" are actually just BSSs, especially the nearest one RX J1856.5-3754 (no NS atmosphere model available can fit its X-ray *and* optical data, Burwitz et al. 2001), since almost no atom appears above a bare quark surface.

Strange stars can be bare and BSSs can exist as compact stars (Xu & Qiao 1998, Xu, Zhang & Qiao 2001). Drifting subpulses of radio pulsars could be an evidence for BSSs (Xu, Qiao & Zhang 1999), which represent the strong binding of particles above pulsar surfaces. Super-Eddington emission of soft $\gamma-$ray repeaters might be another evidence for BSSs (Zhang, Xu & Qiao 2001, Usov 2001a). If further observations with much higher signal-to-noise ratios still find no spectral feature in the thermal components of the sources listed in Table 1, the featureless thermal spectrum should be a new evidence for BSSs.

2. STRANGE STARS: CRUSTED OR BARE?

Current researches show that it is possible to leave a strange star after a core-collapse type supernova explosion. However, it depends on wether the strange star is bare or crusted to distinguish neutron stars and strange stars based on their sharp differences in surface conditions. Although relevant qualitative arguments are addressed separately in many published papers, it is worth summarizing concisely those discussions, with the inclusion of some quantitative estimates and modifications. A protostrange star may be bare due to strong mass ejection and high temperature (Usov 1998), whereas a BSS may still have the possibility to be covered by a crust due to the accretion of (1) supernova fallback and of (2) debris disk. It follows below that such an accretion-formed crust looks probably in no likelihood.

In case (1), as Xu et al. (2001) suggest, due to rapid rotation and strong magnetic field, most of the fallback matter may form temporarily a fossil disk, and the initial accretion onto a star is almost impossible. Recently, 3-D simulations by Igumenshchev & Narayan (2002) show that the gravitational energy of the infall magnetized plasma has to be converted to other energies, and that the initial accretion rate could be reduced significantly. Nevertheless, Xu et el. (2001) proposed another trapping of supernova ejecta by magnetic fields, rather than the Chevalier's (1989) one by gravity. This trapped material with mass $\sim 10^{-15}M_\odot$ could fall back onto the surface to form a massive atmosphere *if* there exits no other force but gravity. However, the radiative pressures of *strong* photon and neutrino emission are not negligible because of high temperature ($T \sim 10^{11} - 10^8$ K, see §3). Only more than years latter could the photon luminosity be smaller than the Eddington one ($L_{\rm Edd} \sim 10^{38}$ ergs/s). A possible scenario could be as follow. The trapped ions, forced by radiation, move along the magnetic lines to an out most region of each line, where these enriched ions go across the field

lines (higher density increases the kinematic energy density), and may merge eventually into debris disk.

Accretion in case (2) was supposed to power the X-ray emission of AXPs and SGRs (e.g., Marsden & White 2001) during the non-stationary "prospellar" phase, since the X-ray powers of these sources are much higher than the energy loss rates of their spindowns. These accretion energy rates $\mathcal{L}$ could be expected $\mathcal{L} < 10^{36}$ ergs/s (the maximum persistent X-ray luminosity of AXPs and SGRs). Can a crust be formed during such accretions? Because of strong fields, infalling matter is funneled toward the polar caps, goes like freefall until feeling the deceleration due to the radiation pressure generated by the accreted material on the caps. Without this halting, a proton could have kinematic energy of ~ 100 MeV near the surface of a BSS, and could thus penetrate the Coulomb barrier (~ 20 MeV) and dissolves. But in a radiation field with energy density U, a hydrogen atom will actually have a back force $f_\mathrm{r} \sim \sigma_\mathrm{T} U$ with σ_T the Thompson cross section. For low accretion limit, such force is not negligible only when atoms are near the hot spot powered by accretion, and the height of this region is about the polar cap radius, r_p. In view of only ε times of the accretion energy has been re-emitted above polar cap (see Appendix), by $f_\mathrm{r} r_\mathrm{p} = GMm_\mathrm{p}/R$, we obtain a critical accretion rate $\mathcal{L}^*$,

$$\mathcal{L}^* = \frac{2\pi G c r_\mathrm{p} M m_\mathrm{p}}{\varepsilon \sigma_\mathrm{T} R} = \frac{9.1 \times 10^{35}}{\varepsilon} M_1 R_6^{-1} P^{-1/2} \ \ \mathrm{ergs\ s^{-1}}, \tag{1}$$

which is $\sim 1/\varepsilon$ times higher than the critical value presented by Basko & Syunyaev (1976). If $\mathcal{L} < \mathcal{L}^*$, an atom may still have enough kinematic energy to penetrate after the deceleration. We expect that the accretion of ISM or fossil disk can also keep a strange star to be bare since $\mathcal{L} < 10^{36}$ ergs/s $< \mathcal{L}^*$. It is very likely that $\mathcal{L}^* > L_\mathrm{Edd}$, since ε can be as small as 10^{-4} (see Appendix). This means that BSSs may also survive some of the accretions with super-Eddington rates. A crust covering a strange star could be formed via accretion if $\mathcal{L} > \mathcal{L}^*$, which ensures no distinction between the faced and magnetospheric radiations of SSs and NSs. But such a high accretion rate might be only possible for binary X-ray sources. Recycled millisecond pulsars could be BSSs as long as the accretion rates $< \mathcal{L}^*$ during their accretion phases.

There may be another way to produce BSSs. A nascent rapid rotating magnetized NS could form with a mass reaching the Oppenheimer limit, but quickly losses its angular momentum via gravitational (driving the rotation-modes unstable) and electromagnetic (magnetic dipole) radiations. A NS central density has to be high enough for a phase conversion to a strange star[1] before the NS is so slow and cool that a super-Oppenheimer mass is possible. Such a strange star should also be bare since 1, the phase transition energy $\gg$ the crust gravitational binding; 2, the photon emission rate $\gg L_\mathrm{Edd}$.

In conclusion BSSs can exist in nature. Probably some of them may act as those X-ray sources in Table 1.

3. COOLING AND THERMAL EMISSION OF BARE STRANGE STARS

We could expect a nascent strange star with thermal energy $\mathcal{E}_\mathrm{i} \gtrsim 10^{52}$ ergs since the gravitational and the degenerate energies are in the same order, $\sim 10^{53}$ ergs, even if other energy sources (e.g., the rotation energy, the phase transition energy) are included. The specific heat of strange quark matter is (e.g., Usov 2001b) $C = C_\mathrm{q} + C_\mathrm{e}$, with $C_\mathrm{q} = 1.9 \times 10^{12} \rho_{15}^{2/3} T_\mathrm{c} \exp(-\Delta/T)[2.5 - 1.7T/T_\mathrm{c} + 3.6(T/T_\mathrm{c})^2]$ ergs cm^{-3}K^{-1}, $C_\mathrm{e} = 1.3 \times 10^{11} Y_\mathrm{e}^{2/3} \rho_{15}^{2/3} T$ ergs cm^{-3}K^{-1}. The specific heat of unpaired electrons dominates, $C_\mathrm{e} > C_\mathrm{q}$, when $T < 7.45 \times 10^9$ K. The electron fraction $Y_\mathrm{e} \sim 10^{-3}$. The energy gap is very uncertain, and whether the color super-conducting (CSC) occurs is therefore still a question. We choose $\Delta = 50$ MeV for next discussion, so a strange star should be in CSC state except for the very beginning of its birth. The critical temperature $T_\mathrm{c} \sim \Delta/2$ in the BCS model. By $\mathcal{E}_\mathrm{i} = CT_\mathrm{i} \cdot 4\pi R^3/3$, one obtains the initial temperature $T_\mathrm{i} \gtrsim 10^{10}$ K, which means strange is very hot soon after supernova explosion.

Effective neutrino emissivity of a newborn hot strange star rapidly expels the thermal energy, making the strange star have a much cooler temperature at which the photon emission dominates. The dividing temperature T_ν is a solution of

$$3 \times 10^{-4} \sigma T_\nu^4 = R\epsilon_\nu(T_\nu), \tag{2}$$

which is $T_\nu \sim 4 \times 10^{10}$ K for typical parameters, where the neutrino emissivity (e.g., Usov 2001b) $\epsilon_\nu = 7.8 \times 10^{-28} \alpha_\mathrm{s} Y_\mathrm{e}^{1/3} \rho_{15} T^6 \exp(-\Delta/T)$ ergs cm^{-3} s^{-1}, and σ is the Stefan-Boltzmann constant. The factor 10^{-4} in Eq.(2) is due to the upper limit on photon emissivity of strange quark matter at energies < 20 MeV (Chmaj et al. 1991). This T_ν estimated is on the high side if CSC does not occur at the very beginning, nevertheless this value implies photon emission almost dominates all over a strange star's life. This conclusion is strengthened if the Usov's (1998) photon emission mechanism is included.

The equation governing a BSS's cooling history is

$$\frac{4}{3}\pi R^3 \cdot C \frac{\mathrm{d}T}{\mathrm{d}t} = -\xi \sigma T^4 \cdot 4\pi R^2, \tag{3}$$

where $\xi \sim 1$ for $T > 10^9$ K at which the Usov mechanism works, whereas $\xi \lesssim 10^{-4}$ for $T < 8 \times 10^8$ K (Usov 2001c). When $T < 7.45 \times 10^9$ K, assuming a constant ξ, Eq.(3) can be solved to be

$$T = T_0(1 + 2\mathcal{J}\xi T_0^2 t)^{-1/2}, \tag{4}$$

where $\mathcal{J} = 3\sigma/(\check{C}_\mathrm{e} R)$, $\check{C}_\mathrm{e} = C_\mathrm{e}/T$, t is the time duration when a BSS cools from temperature T_0 to T. According to Eq.(4), a BSS cools to $T \sim 10^6$ K after $\sim 10^3$ years. However, because of the magnetospheric polar cap heating, powered by the bombardment of downward-flowing particles, a BSS should keep a minimum temperature T_min. As a rough estimate at first, equating the photon emission rate to the pulsar spindown power, $\xi \sigma T_\mathrm{min}^4 \cdot 4\pi R^2 \sim 6.2 \times 10^{27} B_{12}^2 R_6^6 (2\pi/P)^4$, one has $T_\mathrm{min} = 3.4 \times 10^6 R_6 B_{12}^{1/2} P^{-1}$ K. For PSR J0437-4715 and PSR B0833-45, $T_\mathrm{min} \sim 9 \times 10^2 R_6$ eV and $6 \times 10^3 R_6$ eV, respectively. Considering that the photon emission power is $\xi \lesssim 10^{-4}$ times that of a blackbody, these temperatures, modified by a factor of ~ 0.1, are comparable with observations (Table 1).

In fact the minimum temperature is model-dependent, and it is worth to discuss T_min in some pulsar emission

---

[1] This process was supposed to be a candidate of the "center engines" of γ-ray bursts (e.g., astro-ph/9908262).

models. Due to the high binding energy of bare quark surface, the space-charge-limited flow model (e.g., Arons & Scharlemenn 1979) can not work for BSSs. We focus thus on the polar cap heatings in the vacuum polar model (Ruderman & Sutherland 1975) and the outer gap model (Cheng, Ho & Ruderman 1986), both of which are depicted in Xu et al. (2001). The polar heating rate of RS-type gap is $\sim 1.1 \times 10^{31} \gamma_7 B_{12} P^{-2}$ ergs/s, and the minimum temperature is thus $T_{\min}^{\mathrm{RS}} \simeq 3.5 \times 10^6 \gamma_7^{1/4} R_6^{-1/2} B_{12}^{1/4} P^{-1/2}$ K, with $\gamma = 10^7 \gamma_7$ the typical Lorentz factor of the primary particles. If outer gaps exist, the luminosity deposited onto the surface is $\sim 8.2 \times 10^{30} B_{12} P^{-5/3}$ ergs/s, and the correspondence temperature is $T_{\min}^{\mathrm{CHR}} \simeq 3.3 \times 10^6 R_6^{-1/2} B_{12}^{1/4} P^{-5/12}$ K. We see that these three values of $T_{\min}$, $T_{\min}^{\mathrm{RS}}$, and $T_{\min}^{\mathrm{CHR}}$ are almost the same. This is not surprising because, although the total energy deposit fluxes differ, the thermal temperature is the amount flux to the power of 1/4.

As for the AXPs (or SGRs), the thermal energy with temperature $T_{\min}$ can not account for their persistent X-ray emissivity since the observed X-ray power is many orders higher than the energy loss rate of rotarion. Nonetheless there are actually two suggestions for extra energy supplying: magnetism-powered (the so called magnetar model, e.g., Thompson & Duncan 1995) and accretion-powered (e.g., Marsden & White 2001). Both these mechanisms have been widely discussed in literatures recently. Since BSSs can also act as magnetars as long as the dynamo action in proto-strange stars is effective enough (see Xu & Busse 2001), we deem that magnetic field line reconnection on BSS surfaces can also work to produce abundant energy. As discussed in section 2 (see eq.1), accretion in AXPs and SGRs can still keep a strange star to be bare. So it is also possible that AXPs (or SGRs) are accretion powered BSSs. Therefore the energy budget problem of AXPs and SGRs are solved if those two popularly discussed mechanisms are adapted to fit BSSs.

In principle, one can study the thermal radiative properties by comparison of theoretically modelled spectra with that of observations. Unfortunately no emergent spectrum calculation of BSSs appears in literature. The total power of photon emissivity of BSSs was done by Chmaj et al. (1991). Nevertheless we could expect that the spectra could be close to blackbodies, which represents the general apparent of the X-ray spectra observed, since, e.g., for the quark bremsstrahlung radiation mechanism (Chmaj et al. 1991), quarks are nearly in thermal equilibrium by inter-collisions within a depth less than the mean free path (~ 10 fm) of photons with energy $< \hbar\omega_{\mathrm{p}} \sim 20$ MeV. A BSS with surface temperature T may have a slightly harder spectrum than that of a blackbody with $\sim 10^{-1}T$. New fits by BSS emergent spectra may alter significantly the physical quantities derived through the thermal radiations. For example, one powerlaw and only one thermal spectra might be enough to model precisely the observed spectrum of PSR J0437-4715 (Zavlin et al. 2002). Because of this lack of fits, the temperatures and radii listed in Table 1 may not be relevant if we want to obtain observationally the thermal properties (e.g., the temperature distribution) on a BSS surface.

This kind of research may get a real information of photons from quark matter astrophysically, whereas in terrestrial physics, direct photons and lepton pairs have been recognized to be the clearest signatures for quark-gluon plasma (e.g., Cassing & Bratkovskaya 1999). It is worth noting that the BSS thermal photon emission is in the low energy limit, which would thus complement the study of the high energy photons of relativistic nucleus-nucleus collisions. Future observations in various ways may confirm the existence of BSSs, and in return the observational fit of the thermal spectra from the quark surfaces could be used as a test in checking those phenomenological models for quark gluon plasma in strong magnetic fields.

It should be noted that magnetospheric power law components of BSSs are also featureless (Xu & Qiao 1998, Xu et al. 2001), but a neutron star may have magnetospheric line features because of the ions, pulled out from NS surface by the space-charge-limited-flow mechanism, in the open field line region.

4. CONCLUSION & DISCUSSION

An alternative opinion is proposed for the nature of the sources with featureless X-ray spectra observed by Chandra and XMM, which is that these X-ray emitters are simply bare strange stars (BSSs). Possible scenarios to create a BSS are studied, and we find that accretion can not prevent from forming a BSS unless the accretion rate is much higher than the Eddinton one. The cooling and the thermal radiation of a BSS are also discussed, indicating that they are not strongly conflict with observations.

There could be indications for one or two lines at about 40Å and 20Å in RX J1856.5-3754 (van Kerkwijk 2002). This is a real challenge for the BSS idea. If future longer observations with Chandra and XMM confirm the existence, the source is certainly not a BSS, but could be a crusted strange star since stringent constrains on the mass ($M \approx 1M_\odot$) and radius ($R \approx 6$ km) for RX J1856.5-3754 (Ransom et al. 2001) show clearly that it can hardly be modelled by the equations of states of nuclear matter.

The age of PSR J0437-4517 is worth deliberating. A millisecond pulsar could be very hot soon after recycling phase when the polar heat is transported effectively to the other part of BSS due to a small ε. However, r-mode instability may spin down a BSS to an initial period $P_0 \sim 3-5$ ms (e.g., Andersson & Kokkotas 2001), which can have substantial influence on the age calculation by dipolar radiation braking. However P_0 is temperature dependent, and thus relevant to the accretion history. The fastest rotating pulsar, PSR 1939+21, might have a small accretion rate but a long time during its accretion phase. The age of PSR J0437-4517 is much smaller if its $P_0 \sim 5$ ms soon after accretion, and it thus has high temperature today.

This is a critical time in obtaining the thermal spectra from pulsar-like compact stars. Besides Chandra and XMM, more X-ray missions (HETE-II in 2003, Astro-E in 2005) may finally reveal the secrets, including whether some of the sources are BSSs. We are looking forward to the discoveries over the coming years.

APPENDIX: ENERGY RE-EMITTED ON THE POLAR CAPS

The essential difference between the accretion- or rotation-powered energy deposit processes of NSs and BSSs is that part of the energy should be transported to the outsite of the polar caps for BSSs, but not for

NSs (e.g., Xu et al. 2001), since the coefficient of thermal conductivity of electron in the neutron star surface $\kappa^{NS} = 3.8 \times 10^{14}\rho_5^{4/3}$ ergs s^{-1} cm^{-1} K^{-1}, is much smaller than the coefficient of degenerate quark matter $\kappa^{BSS} = \kappa_q^{BSS} + \kappa_e^{BSS}$, with $\kappa_q^{BSS} = 1.41 \times 10^{21}\alpha_s^{-1}\rho_{15}^{2/3}\exp(-\Delta/T)$ ergs s^{-1} cm^{-1} K^{-1} for quark scattering, $\kappa_e^{BSS} = 1.55 \times 10^{23}Y_e\rho_{15}T_9^{-1}$ ergs s^{-1} cm^{-1} K^{-1} for electron scattering (e.g., Blaschke et al. 2001), ρ_5 and ρ_{15} being the densities in unit of 10^5 and 10^{15} g cm^{-3}, respectively, α_s the coupling constant of strong interaction, T the temperature, $T_9 = T/(10^9K)$, the energy gap $\Delta \sim 10 - 100$ MeV, and $Y_e \sim 10^{-3}$ the ratio of numbers of electrons and baryons. A dimensional argument gives out the temperature difference between polar cap and equator for BSSs,

$$\delta T \sim \mathcal{L}/(\kappa^{BSS}R), \tag{5}$$

where $\mathcal{L}$ is the rate of total energy deposit, $R \sim 10^6$ cm is the stellar radius. For $\mathcal{L} \sim 10^{36}$ ergs s^{-1}, one has $\delta T \sim 6.5 \times 10^9 T_9$ K, which is in the same order of polar temperature.[2] This means substantial energy should be dissipate to outside of polar cap in BSS if $\mathcal{L} \lesssim 10^{36}$ ergs s^{-1}. Defining ε to be the re-emission photon fraction of the total energy deposit, we have $1 > \varepsilon > r_p^2/(2R^2) \sim 10^{-4}/P$ if $\mathcal{L} \lesssim 10^{36}$ ergs s^{-1}, where $r_p = 1.45 \times 10^4 P^{-1/2}$ cm is the polar cap radius, P the rotation period. Assuming one-half of the deposit energy being brought away by neutrinos rather than photons in this case, one obtains modified limits for ε: $5 \times 10^{-5}/P < \varepsilon < 0.5$, where the upper limit is for $\mathcal{L} \to +\infty$ and the lower limit for $\mathcal{L} \to 0$.

REFERENCES

Andersson, N., Kokkotas, K.D. 2001, Int. J. Mod. Phys., D10, 381
Arons, J., & Scharlemann, E.T. 1979, ApJ, 231, 854
Basko, M. M., Syunyaev, R. A. 1976, MNRAS, 175, 395
Burwitz, V., Zavlin, V. E., Neuhäuser, R., et al. 2001, A&A, 379, 35
Cassing, W., Bratkovskaya, E. L. 1999, Phys. Rep., 308, 65
Chevalier, R. A. 1989, ApJ, 346, 847
Cheng, K.S, Ho, C., & Ruderman, M. 1986, ApJ, 300, 500
Chmaj, T., Haensel, P., Slomiński, W. 1991, Nucl. Phys., B24, 40
Igumenshchev, I. V., Narayan, R. 2002, ApJ, 566, 137
Juett, A. M., Marshall, H. L., Chakrabarty, D., Schulz, N. S. 2002, ApJ (Letters), in press (astro-ph/0202304)
Lugones, G., Benvenuto, O.G., Vucetich, H. 1994, Phys. Rev. D50, 6100
Marsden, D., White, N. E. 2001, ApJ, 551, L155
Marshall, H.L., Schulz, N.S. 2002, submitted to ApJL (astro-ph/0203463)
Paerels, F., Mori, K., Motch, C., et al. 2001, A&A, 365, 298
Pons, J. A., Walter, F. M., Lattimer, J. M. 2002, ApJ, 564, in press (astro-ph/0107404)
Ransom, S. M., Gaensler, B. M., Slane, P. O. 2001 (astro-ph/0111339)
Romani, R. W. 1987, ApJ, 313, 718

Ruderman, M. A., & Sutherland, P. G. 1975, ApJ, 196, 51
Sanwal, D., Pavlov, G. G., Kargaltsev, O. Y., et al. 2002, in "Neutron Stars in Supernova Remnants", ed. P. O. Slane & B. M. Gaensler (ASP Conference Proceedings), in press (astro-ph/0112164)
Thompson, C., & Duncan, R.C. 1995, MNRAS, 275, 255
Tiengo, A., Goehler, E., Staubert, R., & Mereghetti, S. 2002, A&A, in press (astro-ph/0111304)
Usov, V. V. 1998, Phys. Rev. Lett., 80, 230
Usov V. V. 2001a, Phys. Rev. Lett., 87, 021101
Usov V. V. 2001b, ApJ, 559, L135
Usov V. V. 2001c, ApJ, 550, L179
van Kerkwijk, M. H. 2002, in Proc. Jan van Paradijs Memorial Symposium, ed. E. P. J. Van den Heuvel, L. Kaper & E. Rol (ASP, San Fransisco), in press (astro-ph/0110336)
Xu, R. X., & Busse, F. H. 2001, A&A, 371, 963
Xu, R. X., Qiao, G. J. 1998, Chin. Phys. Lett., 15, 934
Xu, R. X., Qiao, G. J., Zhang, B. 1999, ApJ, 522, L109
Xu, R. X., Zhang, B., Qiao, G. J. 2001, Astropart. Phys., 15, 101
Zhang, B., Xu, R.X ., Qiao, G. J. 2000, ApJ, 545, L127
Zavlin, V. E., Pavlov, G. G., Sanwal, D., et al. 2002, ApJ, in press (astro-ph/0112544)
Zavlin, V. E., Pavlov, G. G., Shibanov, Yu. A. 1996, A&A, 315, 141

[2] In case of no energy dissipated (e.g., for NSs), the polar temperature $T = 2.3 \times 10^6 \mathcal{L}_{30}^{1/4}P^{1/4}$, where $\mathcal{L}_{30} = \mathcal{L}/(10^{30}\text{ergs/s})$. This temperature is an upper limit of that of BSSs.

TABLE 1
"Neutron stars"[a] with X-ray thermal spectrum observed by Chandra or XMM

Name	Period	B-Field (G)	Temperature (eV)[b]	Radius (km)[b]	γ_{pl}[c]	Age (y)
RX J1856.5-3754 (INS)	-	-	20(g), $\sim$ 60(l)	$\leq$ 10(g), 2.2(l)	-	$\sim 10^6$
RX J0720.4-3125 (INS)	8.39 s	-	86(l)	-	-	-
1E 1048.1-5937 (AXP)	6.45 s	Magnetar?	$\sim$ 600(l)	-	$\sim$ 3	-
4U 0142+61 (AXP)	8.69 s	Magnetar?	418(l)	-	3.3	-
PSR J0437-4715 (msPSR)[d]	5.76 ms	3×10^8	181(core), 46.5(rim)	0.1(core), 2(rim)	2.2	4.9×10^6(?)
PSR B0833-45 (Vela)	89.3 ms	3.4×10^{12}	129(l)	2.1(l)	2.7	1.1×10^4
PSR B0656+14 (PSR)	385 ms	4.7×10^{12}	69.0(g), 138(l)	22.5(g), 1.7(l)	-	1.0×10^5

[a]References: Burwitz et al. (2001), Pons et al. (2002), Paerels et al. (2001), Tiengo (2002), Juett et al. (2002), Zavlin et al. (2002), Sanwal et al. (2002), Marshall & Schulz (2002).

[b]"g" and "l" denote for *global* and *local* (e.g., polar-cap) blackbody spectra, respectively.

[c]The photon index of a nonthermal power-law spectrum.

[d]The temperature and radius here are for the fitting of the data with the two-temperature hydrogen polar-caps, but could be qualitatively similar parameters for a two-temperature blackbody polar-cap model.